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A Laboratory Study on Revegetation and Metal Uptake in Native Plant Species from Neutral Mine Tailings

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Abstract *Lygeum spartum, Zygophyllum fabago* and *Piptatherum miliaceum* are typical plant species that grow in mine tailings in semiarid Mediterranean areas. The aim of this work was to investigate metal uptake of these species growing on neutral mine tailings under controlled conditions and their response to fertilizer additions. A neutral mine tailing (pH of soil solution of 7.1–7.2) with high total metal concentrations (9,100 and 5,200 mg kg^{-1} Zn and Pb, respectively) from Southern Spain was used. Soluble Zn and Pb were low (0.5 and <0.1 mg l^{-1}, respectively) but the major cations and anions reached relatively high levels (e.g. 2,600 and 1,400 mg l^{-1} Cl and Na). Fertilization caused a significant increase of the plant weight for the three species and decreased metal accumulation with the exception of Cd. Roots accumulated much higher metal concentrations for the three plants than shoots, except Cd in *L. spartum*. Shoot concentrations for the three plants were 3–14 mg kg^{-1} Cd, 150–300 mg kg^{-1} Zn, 4–11 mg kg^{-1} Cu, and 1–10 mg kg^{-1} As, and 6–110 mg kg^{-1} Pb. The results indicate that neutral pH mine tailings present a suitable substrate for establishment of these native plants species and fertilizer favors this establishment. Metal accumulation in plants is relatively low despite high total soil concentrations.

Keywords Mine tailings · Semiarid climate · Zygophyllum fabago · Piptatherum miliaceum · Lygeum spartum · Phytoremediation

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1 Introduction

Mining activities have deleterious effects on the environment due to the deposition of huge amounts of wastes in the form of mine tailings (Dudka and Adriano 1997). These tailings usually present unfavorable conditions for natural plant establishment such as low pH (Wong et al. 1998) toxic metal concentrations (Norland and Veith 1995; Wong et al. 1998; Ye et al. 2000), high salt content (Norland and Veith 1995; Wong et al. 1998), low water retention capacity (Henriques and Fernandes 1991; Norland and Veith 1995) and deficiencies in nutrients (Wong 2003). In most cases the tailings also have steep slopes that are unstable and prone to erosion (Henriques and Fernandes 1991).

Among all the techniques that can be used for in situ reclamation of mine wastes, revegetation is considered the most suitable for a long term reclamation (Tordoff et al. 2000). Vegetation can provide an effective protection against wind and water erosion (Norland and Veith 1995). The vegetation also may improve the nutrient conditions in the soil (Cobb et al. 2000) and can provide the basis for the establishment of a self-sustaining vegetative cover (Norland and Veith 1995).

For revegetation it is very useful to choose plants that have spontaneously colonized mining sites and that are well adapted to these polluted environments. In semiarid mining zones the establishment of vegetation also requires plant species adapted to drought. The naturally-occurring, metal tolerant vegetation that grows on and around mining zones in arid and semiarid regions has been studied extensively (Alvarenga et al. 2004; Álvarez-Rogel et al. 2004; Flores-Tavizón et al. 2003; García et al. 2003; Leita et al. 1989; Melendo et al. 2002). Tolerant plant species can spread easily in these environments because of lack of competitors (Macnair 1987).

Lygeum spartum L. (Family *Poaceae*), is a widespread grass in the Mediterranean zone that can tolerate extreme conditions of aridity, salinity and high temperatures (Diaz and Honrubia 1993). This species has been found on acid mine tailings ($pH < 5$) from Southern Spain (Conesa et al. 2006) but did not colonize neutral mine tailings in the same zone.

Piptatherum miliaceum (L.) (Cosson or smilo grass, Family *Poaceae*) is another species that grows naturally in these polluted ecosystems (Melendo et al. 2002; García et al. 2003; Conesa et al. 2006). It is commonly found in pastures and open grassy places throughout the Mediterranean region and has been introduced worldwide (García et al. 2004a). Young plants are also eaten by cattle (Conesa 2005). Both, *L. spartum* and *P. miliaceum*, have a strong rhizomatic root system which facilitates a suitable fixation of the plant in the soil and reduces erosion (Conesa et al. 2003).

Zygophyllum fabago L. (Syrian beancaper), belonging to the Family *Zygophyllaceae*, is frequently found in the arid regions of Southern Europe and in the arid zones of the Mediterranean coast region (Tutin et al. 1968). It is considered an invasive plant species of crop lands (USDA 2005) that in extreme cases can dominate the vegetation excluding the native plant species (Davison and Wargo 2001). Conesa et al. (2006) and Melendo et al. (2002) have reported the presence of *Z. fabago* on mine tailings in Southern Spain. Conesa et al. (2003) reported good colonization and establishment of *Z. fabago* in the tailings. However, in spite of the high germination percentage, its subsequent establishment was not successful and few plants survived.

Some studies have evaluated metal uptake of *P. miliaceum* and *Z. fabago* in hydroponic culture (García et al. 2004a, b). Although these experiments allow for better control of growing conditions compared to soil experiments, they are not a realistic model of the natural conditions where the effect of soil buffering capacity influences compound availability to plants (Robinson et al. 1998).

The Cartagena-La Unión Mining District in Southeast Spain (Fig. 1) covers an area of 50 km^2 and contains 48 acidic and neutral mine tailings (Ortega et al. 1993) with a surface of 160 ha (Martínez-Orozco et al. 1993). Some previous studies in this zone have detected the presence of plant species that grow on mining wastes and show relative tolerance to high heavy metal concentrations (Álvarez-Rogel et al. 2004; García et al. 2003). Different types of vegetation colonize their surfaces (Conesa et al. 2006). Conesa et al. (2007) evaluated the response of *L. spartum* to calcite amendments and fertilizer application in acid mine tailing substrates, observing no effect of fertilizer addition and better growth with calcite addition.

Tailings with neutral pH seem to have less constraints to plant growth than acid tailings since the pH is more suitable for plant growth. Nevertheless, the deficiencies in nutrients, the phytotoxic metal concentrations, and high salt content may adversely affect plant establishment and growth.

The purpose of this work was to evaluate growth and metal uptake in *L. spartum, P. miliaceum* and *Z. fabago* growing in neutral mine tailing under controlled laboratory conditions and to investigate the response of these plant species to fertilizer additions. The results are then compared to previous hydroponic cultures or plants grown in the field. These plant species are very interesting for phytostabilization of mine tailings due to their adaptation to drought and fast spreading characteristics.

Fig. 1 Location of the studied area

2 Materials and Methods

2.1 Study Site

The Cartagena-La Union Mining District (Fig. 1) constituted an important mining nucleus for more than 2,500 years, ceasing activity in 1991. The terrain of this area is low lying (<400 m above sea level), but with steep slopes because of its proximity of the coast. The climate is typically Mediterranean with an annual rainfall around 250–300 mm concentrated during spring and autumn. The annual average temperature is 18°C. Therefore, it can be regarded as a semiarid region.

The ore deposits of this zone have iron, lead and zinc, as the main metal components (Oen et al. 1975). As a consequence of the long period of mining activity, large volumes of wastes were generated during the mining and smelting processes (Conesa 2005; Martos-Miralles et al. 2001). Historically, these wastes were dumped into watercourses, filling riverbeds and contaminating their surroundings. In order to remedy this situation, the Government in 1955 prohibited mining companies from dumping wastes on the ground to form tailings (Vilar et al. 1991).

2.2 Soil

Soil samples from “El Gorguel” mine tailing -U.T.M. X 687 480 m, Y 4 162 800 m, Z 135 m; length: 200–300 m, width: 90–100 m, height: 20–30 m, volume: 750,000 m^3 (IGME 1999)-, located on the “El Gorguel” dry river, were taken from the first 40 cm in different points homogenously distributed in the tailing. All soil samples were mixed (resulting in one homogenized sample per zone), air dried, sieved through 2 mm and stored in plastic bags. Total metal concentrations in mine tailing substrate used for this study have been reported in previous studies (Conesa 2005; Conesa et al. 2006) and are summarized in Table 1.

2.3 Pot Experiment

One kilogram of soil was placed into plastic pots (1 l volume). For each of the three plant species (*L. spartum*, *P. miliaceum* and *Z. fabago*) a fertilized

Table 1 Soil properties of "El Gorguel" tailing according to Conesa (2005) and Conesa et al. (2006): pH; Electrical Conductivity of the saturated extract (E.C.); Cation Exchange Capacity (C.E.C.); % Organic Carbon (%O.C.); % Total Nitrogen; % of clay, silt and sand; total and soluble metal concentrations

pH	E.C.	C.E.C.	O.C.	T.N.	clay	silt	sand	Total metal content					Soluble metal in H_2O				
								Cu	Zn	Cd	Pb	As	Cu	Zn	Cd	Pb	As
	dS m^{-1}	cmol(+) kg^{-1}	%					mg kg^{-1}					mg kg^{-1}				
7.2	8	9	0.4	0.018	5	22	73	84	9,100	34	5,200	350	<0.5	2.3	<0.5	<2.5	na

na: not available.

and a non-fertilized treatment with four repetitions was made. The soil was kept close to field capacity by adding ~300 ml water per week (every 2–3 days). The fertilizer (80 N, 80 P, 110 K, 25 Mg in mg kg^{-1} soil) was added with the irrigation water: 30% were added in the first week, 20% in the second and 10% in each following week until 100% was reached. KNO_3, KH_2PO_4, NH_4NO_3, and $Mg(NO_3)_2 \cdot 6H_2O$ were used as chemicals. The plants were grown from seeds that were taken directly from the "El Gorguel" tailing, where they naturally grow. Seeds were pregerminated in Petri dishes with wet filter paper with Millipore water. Germination in Petri dishes was around 70% for *Z. fabago* and 50% for *L. spartum* after 7 days while it was 30% for *P. miliaceum* after 14 days. Seedlings were maintained in small pots with the tailing substrate during one week. Afterwards, two healthy plants of *Z. fabago* and one of *P. milicaeum* and *L. spartum* were planted in each pot. The plants were grown in a climate chamber for 8 weeks with a light cycle of 16 h light- 8 h darkness and controlled humidity (50–90%) and temperature (16/23°C night/day).

2.4 Soil Solution Samples

Samples of soil solution were taken from eight pots of each treatment (fertilizer/no fertilizer) using Rhizon Flex soil moisture samplers (Rhizosphere Research Products, Wageningen, The Netherlands) which were installed at an angle of 45° in each pot. Soil solution samples were taken at the middle of the experiment (fourth week after planting) and stored in plastic tubes at 5°C. The following analyses were made: pH using a 691 pH Meter (Metrohm); electrical conductivity using a conductivity meter WTW LF318/SET; anions using an IC20 Ion Chromatograph (Dionex); and cations using ICP-OES (Vista-MPX Varian) for Pb, Cu, Cd, Zn and As and Flame AAS (SpectraAA 220/FS, Varian) for Ca, Mg, Na and K.

2.5 Plant Analyses

The plants were harvested in the eighth week of the experiment, washed with deionised water, and dried at 65°C. Shoots and roots were separated prior to grinding (RETSCH Schieritz und Hauenstein AG). The dry weight of plants was obtained for individual plants. For the metal content analyses from *Z. fabago* we obtained one representative sample per pot by combining the individual plants. These samples were digested with 2 ml H_2O_2 (30%), 5 ml HNO_3 (65%) and 2 ml H_2O using microwaves (MLS-1200 MEGA ETHOS). Afterwards, the solution was diluted using Milipore water to 25 ml. Cu, Zn, As, Pb and Cd were measured by ICP-OES (Vista-MPX Varian). Quality control was carried out using the Certified Reference Material of the Community Bureau of Reference BCR No 62 (*Olea europaea*).

All Statistical analyses (ANOVA and LSD test) were carried out with Systat 10.2 (SYSTAT 2002). Differences at $P < 0.05$ level were considered significant.

3 Results

3.1 Soil Solution

The soil solution pH was 7.1 for the unamended sample and dissolved Cu, Cd, Pb and As were below the detection limit of 0.1 mg l^{-1} (Table 2). Dissolved Zn was 0.47 mg l^{-1}. The salt concentrations were very high with sulfate, chloride, Na and Ca being the most important anions and cations.

Sulfate concentration exceeded 1,440 mg l^{-1} (30 meq l^{-1}), which Alarcón-Vera (2004) considered

Table 2 Soil solution concentrations of anions and cations in mg l^{-1}

Parameter		No fertilizer n=8	Fertilizer n=8
pH		7.1(<0.1)a	7.2(0.2)a
E.C. (dS m^{-1})		11(2.7)a	14(4.1)a
Metals	Na	1,400(440)a	2,000(760)a
	Mg	850(220)a	1,200(460)a
	K	38(6)a	110(9)b
	Ca	520(67)a	500(71)a
	Cu	<0.1	<0.1
	Zn	0.47(0.06)a	0.55(0.09)b
	Cd	<0.1	<0.1
	Pb	<0.1	<0.1
Metalloid	As	<0.1	<0.1
Anions	Cl-	2,600(1,500)a	3,900(2,100)a
	SO_4^{2-}	4,900(2,100)a	6,200(3,000)a

Values in brackets are standard deviation. Different letters indicate significant differences ($P < 0.05$).

as phytotoxic to plant growth. Chloride also surpassed the limit established by the same author at 355 mg l^{-1} (10 meq l^{-1}) with a concentration of over 2,600 mg l^{-1}.

An excess of soluble Mg in relation to Ca was observed. Alarcón-Vera (2004) considered that ratios of exchangeable Ca:Mg below 1 meq meq^{-1} imply excess of magnesium and may cause negative effects for plant nutrition. The same author also evaluated that ratios of exchangeable K:Mg below 0.2 meq meq^{-1} are a possible cause of nutrition problems because of antagonism, a value that was not reached in the sample.

The fertilizer application had a significant effect on K concentration while for all other major cations and anions the concentrations differences were not significant compared to treatments without fertilizer (Table 2). Dissolved Zn was slightly higher.

3.2 Plant Growth

The three plant species had a satisfactory growth in all the pots even though the growth pattern of each species was different. While *Z. fabago* showed fast growth, *L. spartum* and *P. miliaceum* grew more slowly. The plants without fertilizer showed less

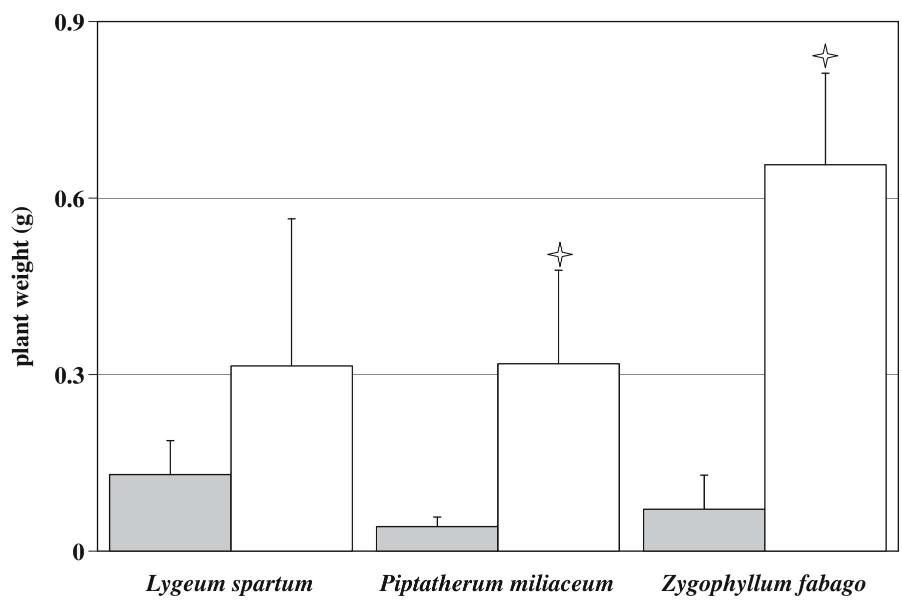

Fig. 2 Dry weight of the plants from fertilized (*white columns*) and unfertilized (*grey columns*) treatments. *Bars on columns* are standard deviation, n = 4 for *L. spartum* and *P. miliaceum* and n = 8 for *Z. fabago*. *Stars above columns* indicate that fertilization caused a significant increase of the weight

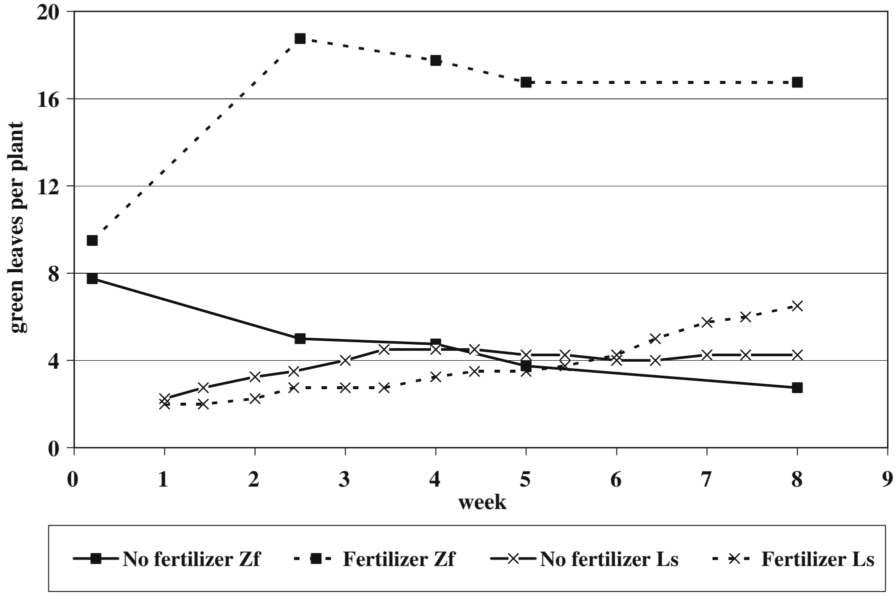

Fig. 3 Evolution in number of green leaves (*total leaves minus chlorotic ones*) per plant of *Z. fabago* (Zf) and *L. spartum* (Ls)

growth than the fertilized ones, although in the case of *P. miliaceum* this higher growth resulted in weak plants (vigour) and some stalks fell down.

For *P. miliaceum* and *Z. fabago* the fertilizer addition caused a significant increase ($P < 0.05$) in plant weight in the fertilizer treated pots (Fig. 2). In the treatment with fertilizer addition, *Z. fabago* had about 10 times more dry weight than without fertilizer (Fig. 2). Moreover, the *Z. fabago* plants with fertilizer addition produced 4–7 times more green leaves (total leaves minus chlorotic ones) after two weeks of the experiment (Fig. 3). However, the effect of fertilizer in increasing the weight was not seen for *L. spartum* ($P > 0.05$). For this species there was also no large difference in the number of leaves between fertilized and non-fertilized pots even though a tendency for higher number of leaves could be seen in the fertilized ones (Fig. 3).

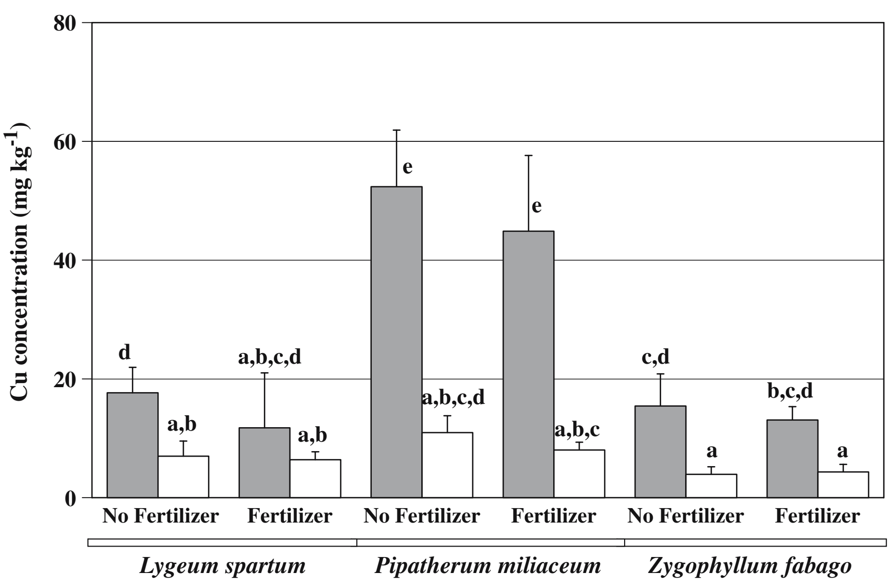

Fig. 4 Cu accumulation in roots (*filled columns*) and shoots (*white columns*) for the different treatments in the three plant species studied. *Bars on columns* are standard deviation ($n = 4$). *Different letters* indicate significant differences ($P < 0.05$)

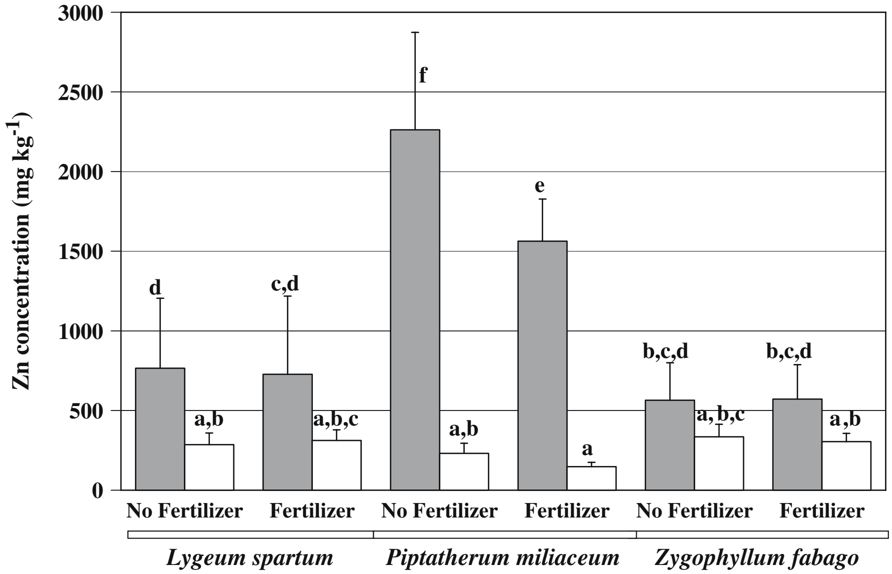

Fig. 5 Zn accumulation in roots (*filled columns*) and shoots (*white columns*) for the different treatments in the three plant species studied. *Bars on columns* are standard deviation ($n = 4$). *Different letters* indicate significant differences ($P < 0.05$)

3.3 Metal Uptake

3.3.1 Zygophyllum Fabago

The fertilizer addition caused no statistically significant effect ($P > 0.05$) on metal uptake in shoots (Figs. 4, 5, 6, 7 and 8). At both treatments the Cu concentration was around 4 mg kg^{-1}, Zn 300–330 mg kg^{-1} and Cd 7 mg kg^{-1}. On the other hand, the fertilizer addition generated a decrease of the As and Pb concentration although these differences were not significant ($P > 0.05$) (Figs. 7 and 8).

All the plants of *Z. fabago* showed higher metal concentration in roots compared to shoots although these difference were only significant ($P < 0.05$) for Cu and Cd (Figs. 4 and 6 respectively). The highest values were reached for Zn with concentrations around 500–600 mg kg^{-1}. There was no strong effect of the fertilizer addition on Zn (560–570 mg kg^{-1}) and Cu (15–13 mg kg^{-1}) concentration in the roots. However, the Cd concentration in roots increased by 50% (from 78 to 122 mg kg^{-1}) and this increase was statistically significant ($P < 0.05$). On the other hand, the fertilizer addition generated a decrease of the As and Pb

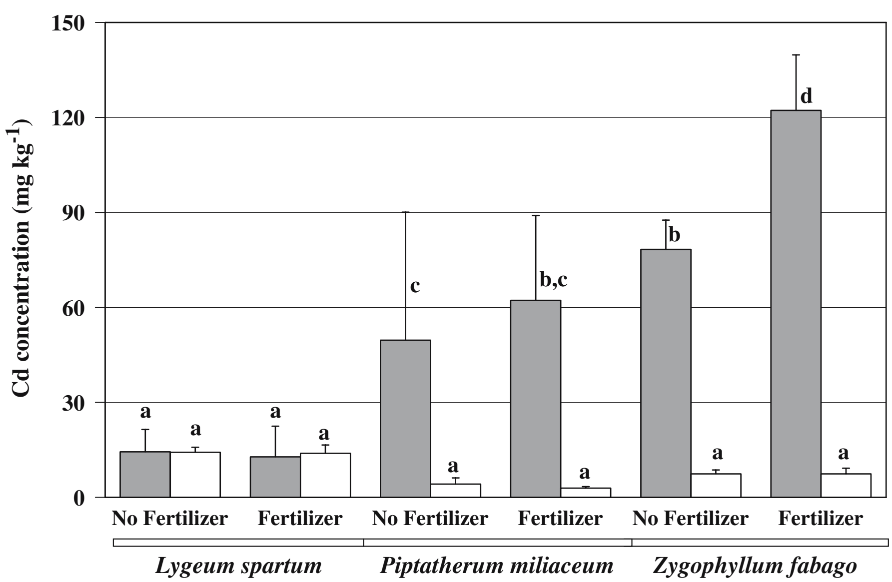

Fig. 6 Cd accumulation in roots (*filled columns*) and shoots (*white columns*) for the different treatments in the three plant species studied. *Bars on columns* are standard deviation ($n = 4$). *Different letters* indicate significant differences ($P < 0.05$)

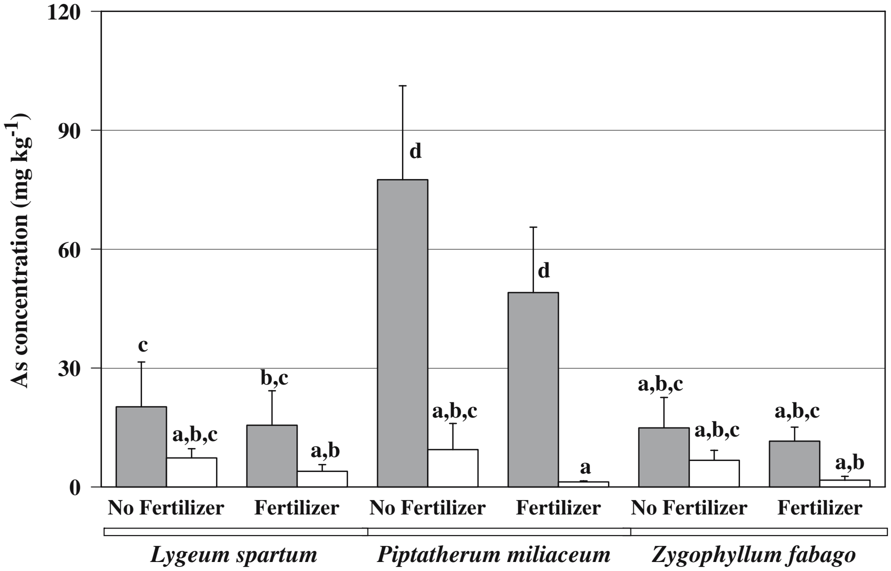

Fig. 7 As accumulation in roots (*filled columns*) and shoots (*white columns*) for the different treatments the three plant species studied. *Bars on columns* are standard deviation ($n = 4$). *Different letters* indicate significant differences ($P < 0.05$)

concentration (Figs. 7 and 8) with a smaller decrease for roots (25–35%) compared to the shoots (75–80%).

3.3.2 Lygeum Spartum

The fertilizer addition caused no significant differences ($P > 0.05$) of metal uptake even though in the fertilized pots the metal concentration was slightly lower. Shoot metal concentrations were lower than root concentrations except for Cd which had similar concentrations for both (14 mg kg^{-1}) (Fig. 6). Metal uptake in *L. spartum* reached similar values for shoots and roots for Pb, As, Cu and Zn, in relation to *Z. fabago*. However there were significant differences ($P < 0.05$) between these two plant species for Cd content in roots.

All the metal concentrations in *L. spartum* roots were much lower and statistically different ($P < 0.05$) from *P. miliaceum*. However these differences did not occur for shoots ($P > 0.05$).

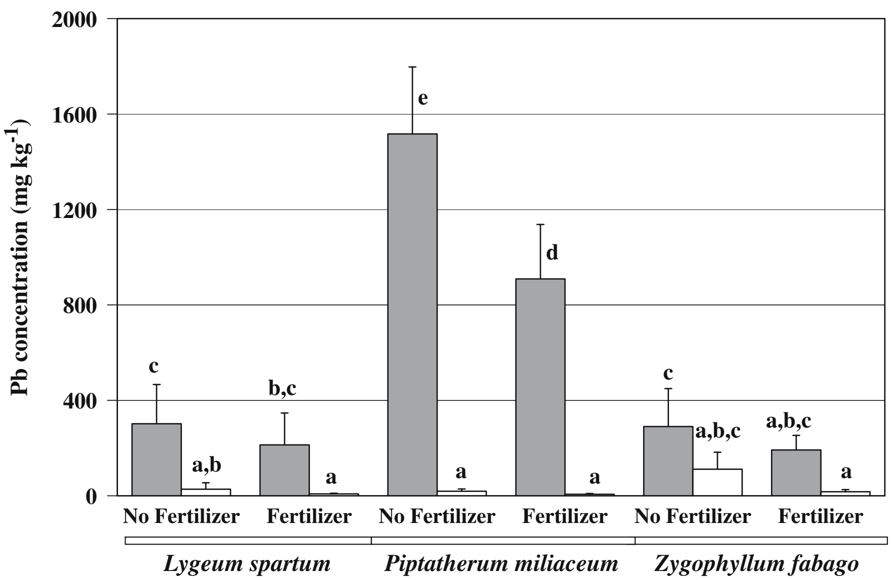

Fig. 8 Pb accumulation in roots (*filled columns*) and shoots (*white columns*) for the different treatments in the three plant species studied. Bars on columns are standard deviation ($n = 4$). Different letters indicate significant differences ($P < 0.05$)

3.3.3 Piptatherum Miliaceum

P. miliaceum accumulated more As, Cu, Zn and Pb and less Cd in the roots than *Z. fabago* (Figs. 4, 5, 6, 7 and 8). Fertilizer addition had a similar effect than in *Z. fabago* and *L. spartum* and the metal concentrations were generally lower, except for Cd. Zn reached the maximum value of all the plants and treatments in the control soil with root concentrations of around 2,000 mg kg^{-1}. The maximum Pb root concentration was reached in the control soil too, with about 1,500 mg kg^{-1} (Fig. 8). *P. miliaceum* had five times more As (Fig. 7) in roots than *Z. fabago* and *L. spartum*.

Shoot concentrations of *P. miliaceum* were higher for Cu, similar for As and lower for Zn, Cd and Pb than for *Z. fabago* and *L. spartum*, although these differences were not statistically significant ($P > 0.05$). However, all the values of metal concentrations in roots of *P. miliaceum* were statistically different ($P < 0.05$) in relation to the other two plant species studied.

4 Discussion

4.1 Plant Growth

In "El Gorguel" soil high salinity and high total heavy metal concentrations seem to be the major constraints to facilitate plant growth. Anion concentrations in soil solution are very important to determine the soil quality since these compounds are not retained by surfaces and they are therefore fully available for the roots. Chloride is directly toxic due to its high mobility and transport to the physiologically most actives parts of the plant (Alarcón-Vera 2004). Sulfate has more a limiting action on plant Ca uptake than a direct toxic effect. It increases the uptake of Na and K and also contributes to the increase of the osmotic pressure (Alarcón-Vera 2004). The high levels of chloride and sulfate that *Z. fabago, L. spartum* and *P. miliaceum* tolerate without showing toxic effects make them salinity tolerant.

The fertilizer addition facilitated the establishment of the plants. Nevertheless, *Z. fabago* had better response to fertilizer than *P. miliaceum* and *L. spartum*. *P. miliaceum* formed weak stalks in the presence of fertilizer. Probably this was due to the high nitrogen content that may favor fast growth. However, the application of fertilizer with less nitrogen content might avoid this problem.

4.2 Metal Uptake

The plants that grew in the fertilized pots showed lower metal concentrations than in non-fertilized pots, probably because of the higher biomass and the phytodilution effect. The metal concentrations in the shoots observed for *Z. fabago* in the pot experiment are lower than the levels that Conesa et al. (2006) measured in wild exemplars of the same species growing at mine tailings in SE Spain (Table 3). The Cu and Zn concentrations of *P. miliaceum* measured in the field were similar to the levels observed in the laboratory experiment. For Pb more data with a larger variation are available for the field and most values are higher than the values found in the laboratory.

Root concentrations of *Z. fabago* measured in the field were generally much higher than the values obtained in the pot experiment but only few data are available from the field. Melendo et al. (2002) for example reported Pb levels in roots of *Z. fabago* of over 2,000 mg kg^{-1}. With the exception of Zn in roots, concentrations reported in this study were lower than accumulation values for two plant species, *Z. fabago* and *P. miliaceum* in hydroponic experiments reported by García et al. (2004a, b).

The Zn and Cu concentrations in shoots of wild exemplars of *L. spartum* that grew in acid mine tailings from the same Cartagena-La Unión Mining District (Conesa et al. 2007) were approximately 50% lower than in our pot experiment. However, the Pb content was 50% higher. The metal accumulation in roots of *L. spartum* was higher in the pot experiment than in the field. However, under controlled conditions and acid tailing substrates the levels were higher than under the same conditions but with the neutral tailing substrates. Finally, when *L. spartum* was grown under controlled conditions in limed acid substrate the metal uptake was comparable to our study.

The differences in metal uptake between field and controlled conditions may be attributed to the different physiologic state of plants and the modification of the soil properties and climate parameters under controlled conditions (Conesa et al. 2007).

Shoots from plants of our experiment surpassed the concentrations that Barceló and Poschenrieder (1992) considered normal in shoots when plants grow in non-polluted sites for Cd (0.05–0.7 mg kg^{-1}), Pb (10 mg kg^{-1}) and Zn (25–150 mg kg^{-1}) but they are in the same range for Cu (5–20 mg kg^{-1} Cu). In this way, a

Table 3 Metal accumulation for *Z. fabago* and *P. miliaceum* in plants that grow in field in mining wastes and values of accumulation reached in hydroponic experiments with inert substrate in the bibliography

Plant species	Site	Roots			Shoots			Reference
		Cu	Zn	Pb	Cu	Zn	Pb	
Piptatherum miliaceum	Laboratory, pot experiment	42–55	1,500–2,200	900–1,500	8–11	150–230	6–19	This study
	Laboratory, hydroponic experiment	–	1,711	6,260	–	2,098	1,919	García et al. (2004a)
	SE Spain, mine tailing	–	–	1,121	–	–	129	Melendo et al. (2002)
	SE Spain, mining soil	–	–	9,958	–	–	981	Melendo et al. (2002)
	SE Spain, mine tailing “El Gorguel”	–	–	–	3	135	34	Conesa et al. (2006)
	SE Spain, riverbed with mining wastes	–	–	800	–	–	160	García et al. (2003)
Zygophyllum fabago	Laboratory, pot experiment	13–15	560–570	190–290	4–29	300–430	110–620	This study
	Laboratory, hydroponic experiment	–	1,500	2,500	–	3,300	1,100	García et al. (2004b)
	SE Spain, mine tailing “El Gorguel”	–	–	–	6	406	108	Conesa et al. (2006)
	SE Spain, mine tailing “El Lirio”	–	–	–	7	528	163	Conesa et al. (2006)
	SE Spain, mining soil	–	–	2,241	–	–	50	Melendo et al. (2002)
Lygeum spartum	Laboratory, pot experiment	12–18	730–765	210–300	6–7	285–310	2–27	This study
	Laboratory, pot experiment with acid tailing substrate	66	3,450–3,600	175	40	4,200–4,400	62	Conesa et al. (2007)
	Laboratory, pot experiment with limed tailing substrate	16–22	400–500	180–270	8	230	13–16	Conesa et al. (2007)
	SE Spain acid tailing soil	6	170	125	3	175	55	Conesa et al. (2007)

Data are in mg kg^{-1}.

continuous ingestion of these plant species by cattle and wild fauna could cause problems for metal accumulation in the food chain, although more studies have to be done in relation to the bioavailability of the pollutants, since total metal concentrations may not reflect the real risk. However, due to the high total metal concentrations in the soil the site would need to be fenced and hence this food-chain transfer would be small.

4.3 Bioconcentration and Accumulation Factor

The bioconcentration factor (Mattina et al. 2003) for roots (ratio between metal concentration in roots and metal in soil) and for shoots (ratio between metal concentration in shoots and metal in soil) expresses the ability of the plants to accumulate metals from the soil. This factor was below 0.2 for all the metals except for Cd where it reached values between 0.2–0.8 in shoots and 0.4–3.6 in roots. Values below 0.2 are considered normal by McGrath and Zhao (2003) when plants are grown on polluted materials.

The accumulation factor (Fitz and Wenzel 2002), also called translocation factor (Mattina et al. 2003), is the ratio between the concentration of metals in shoots and roots, and defines the effectiveness of the plant to translocate the metals to the shoots. Tolerant plants have values less than 1 and hyper-accumulators higher than 1. In our case all the accumulation factors were below 1 with exception of *L. spartum* and Cd that had values of 1. This means that the three investigated plant species can be considered tolerant and therefore may be an interesting option to revegetate neutral pH tailings in semiarid regions. The three species are already adapted to semiarid conditions and integrated in the semiarid Mediterranean ecosystem. This avoids one of the problems that some phytoremediation programs generate because of the introduction of non-native plant species in the ecosystem (Wolfe and Bjornstad 2002). Therefore, the studied plants present a specific solution for a certain climate, soil and geographical location that may restrict their use in phytostabilization works to the Mediterranean area.

Z. fabago has also been investigated because of its allergenic properties (Belchí et al. 1997). It may be important to take into account this aspect if the soil to remediate is near urban zones and exposed to dominant winds.

5 Conclusions

Zygophyllum fabago exhibits a good adaptation to heavily polluted neutral mine tailings even when the salinity of the soil is high. The metal uptake into shoots is relatively small. Therefore, this plant can be considered an interesting option to revegetate neutral pH mine tailings. However, its allergenic properties may require that this species has to be used far from populations and not-exposed to dominant winds.

Piptatherum miliaceum is another species that may be used in order to revegetate neutral soils with high heavy metal concentrations in semiarid climates. Metal accumulation in roots is high but the transfer to shoots is restricted. This decreases the risk of metals entering into the food chain.

Lygeum spartum has a similar behavior than *P. miliaceum* but the metal uptake ranges are closer to *Z. fabago*.

Fertilizer addition can improve the establishment of these plant species in the early stages of their growth and therefore it can be considered a promising tool to get a successful revegetation of mine tailings with similar characteristics in semiarid zones.

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